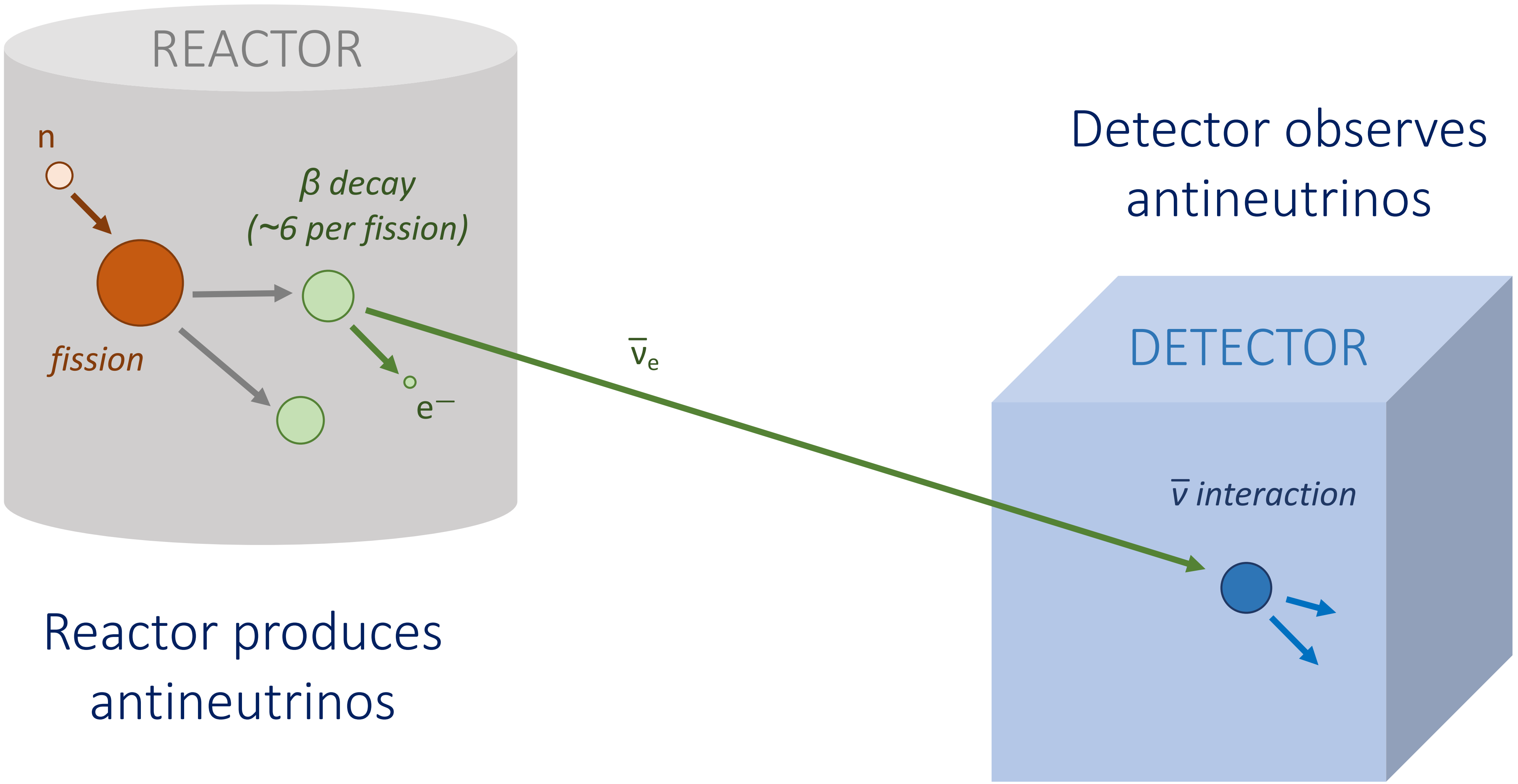
“Reactor Antineutrino 101”

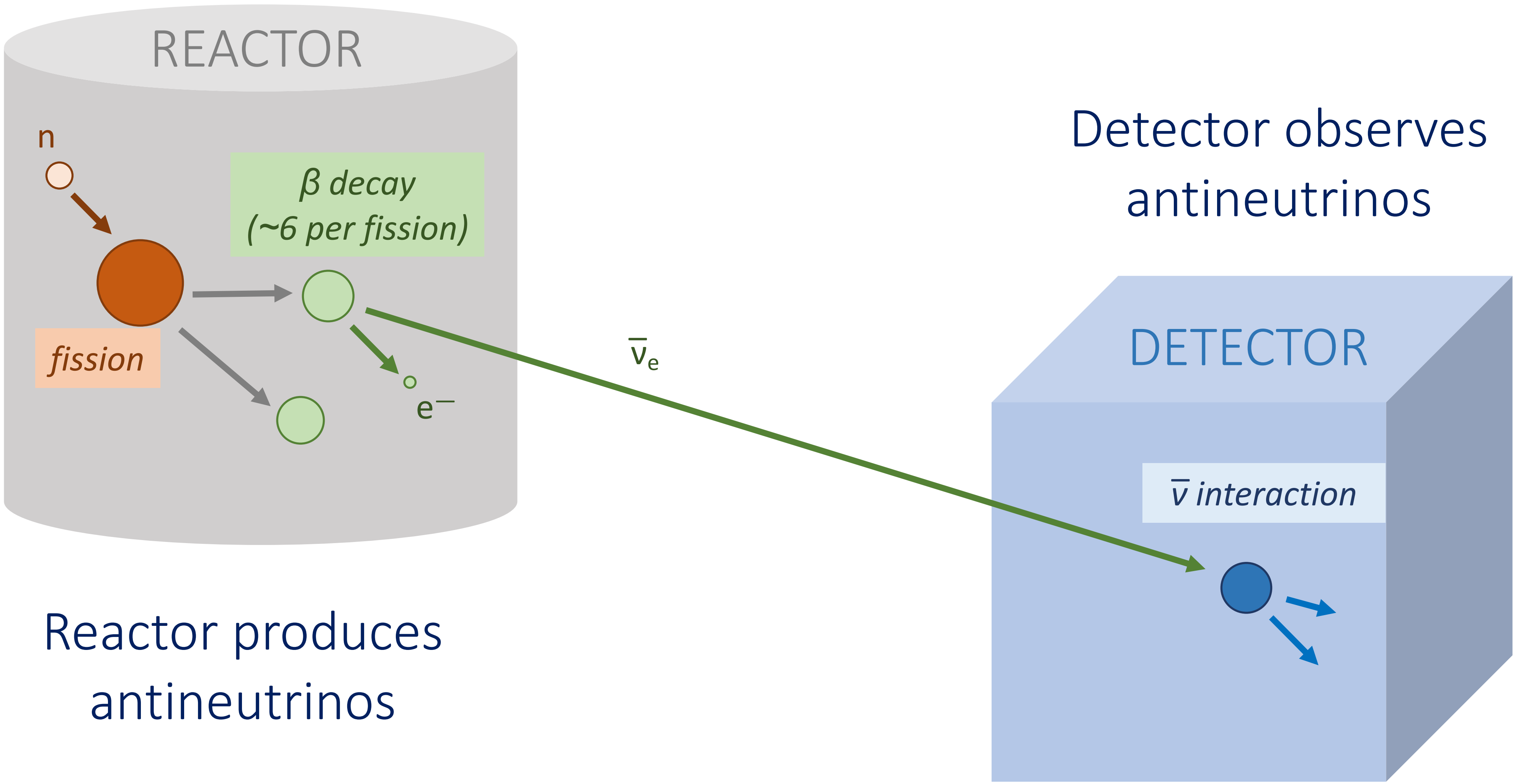
Rachel Carr (MIT)

WoNDRAM — June 21, 2021

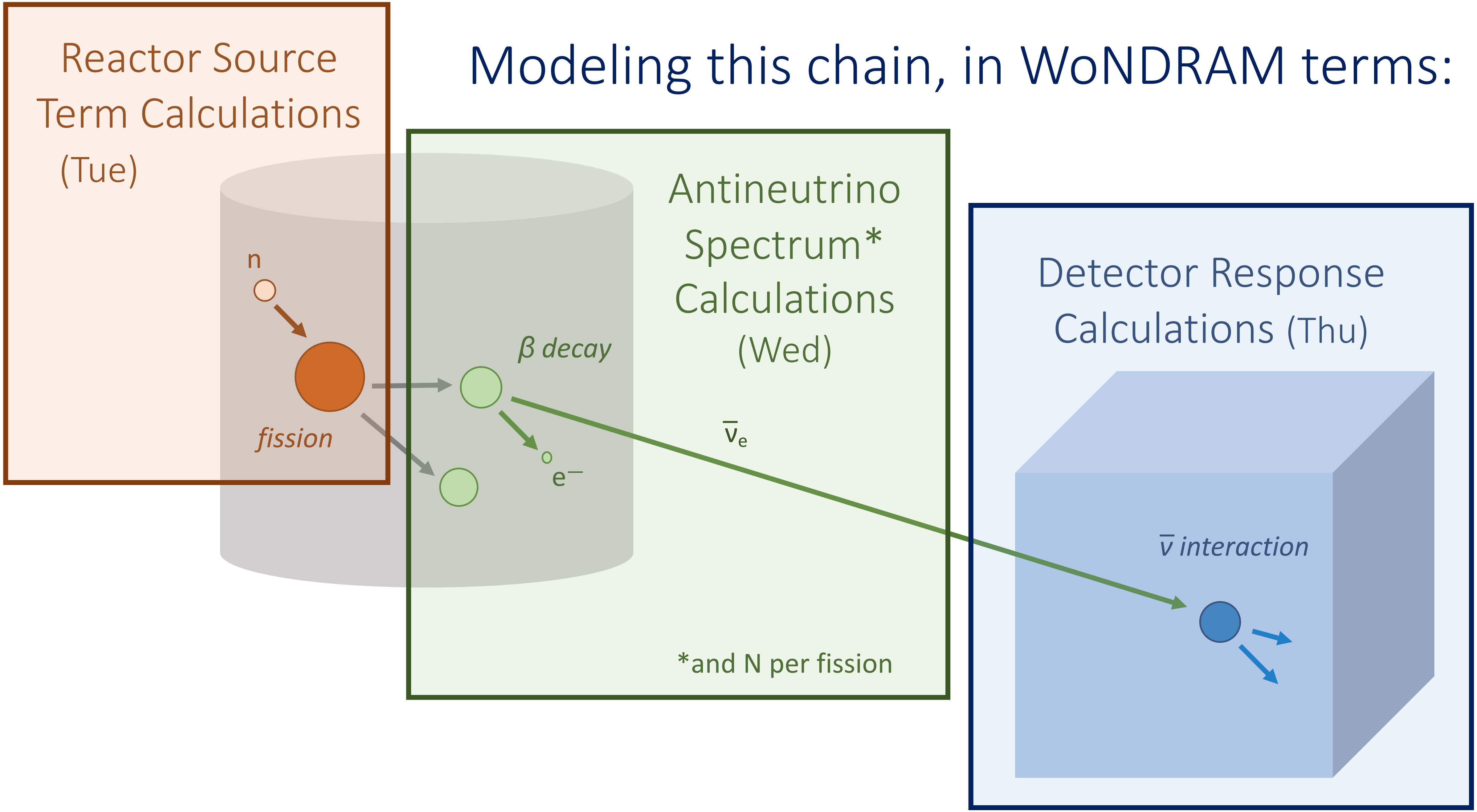
In any reactor antineutrino experiment/application:



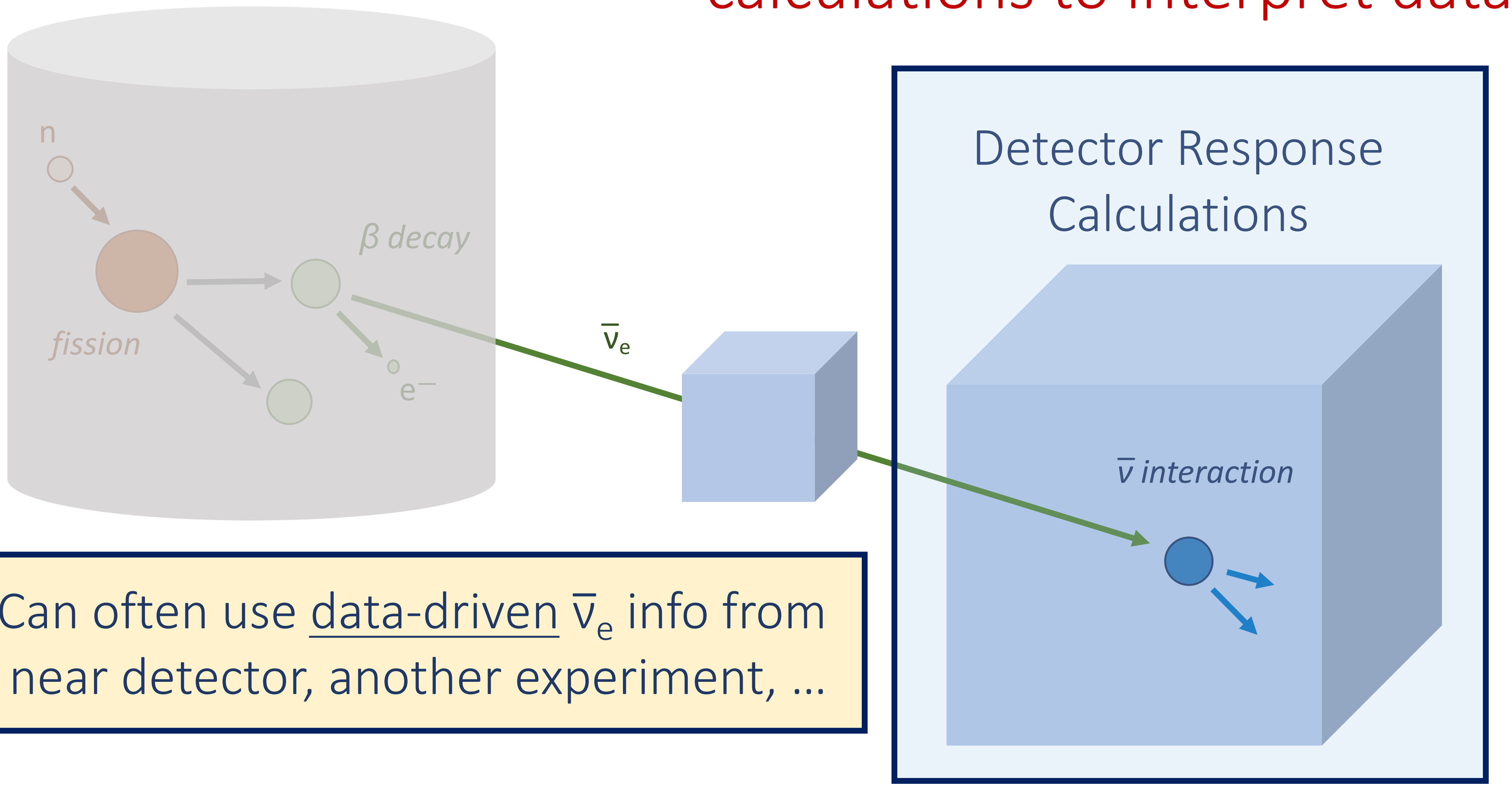
In any reactor antineutrino experiment/application:



Modeling this chain, in WoNDRAM terms:

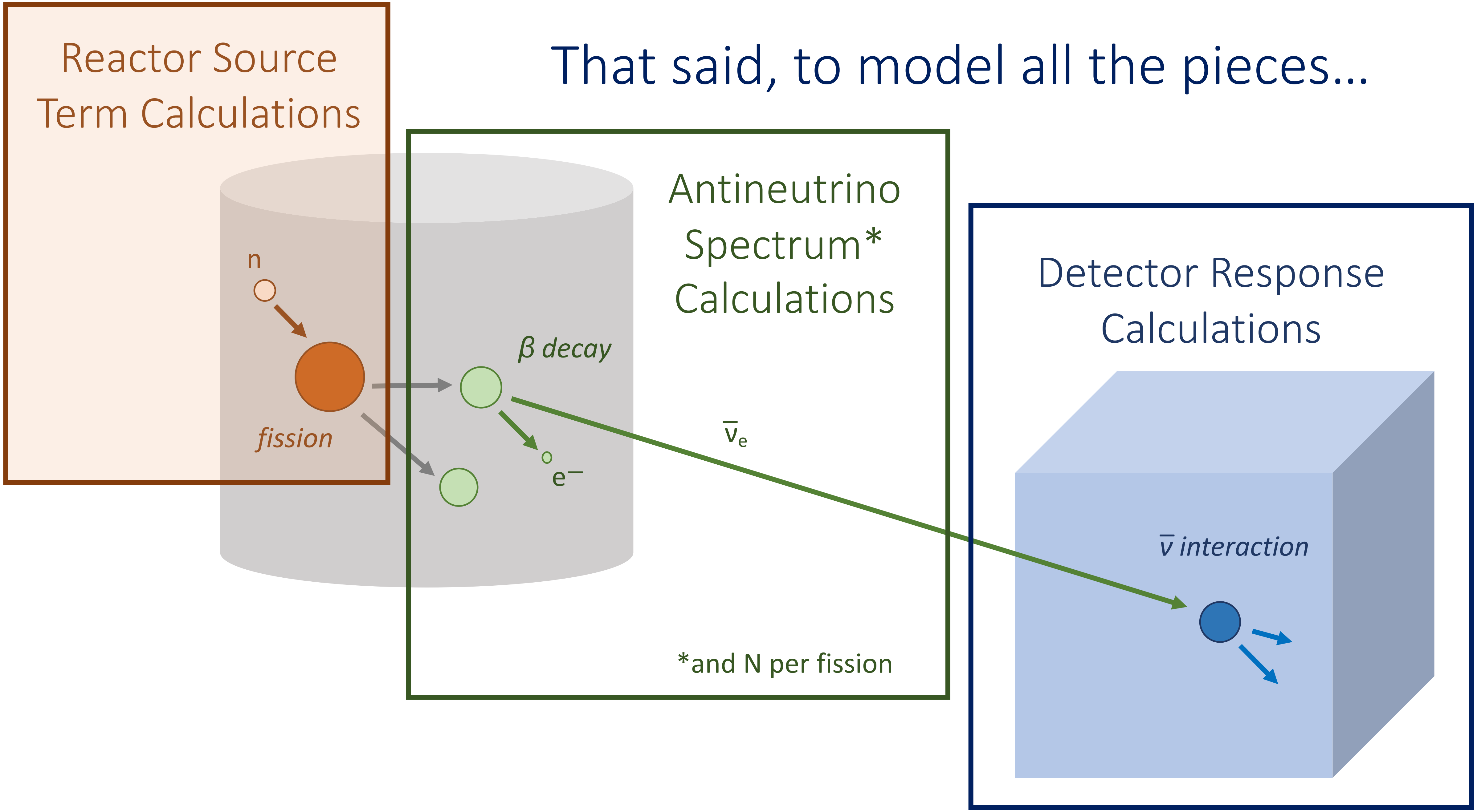


Note: Do not always need Reactor Source & Antinu Spectrum calculations to interpret data



Can often use data-driven $\bar{\nu}_e$ info from near detector, another experiment, …

That said, to model all the pieces…



Reactor Source Term Calculations

- How many fissions are occurring in each isotope in the reactor (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, …) per unit time?

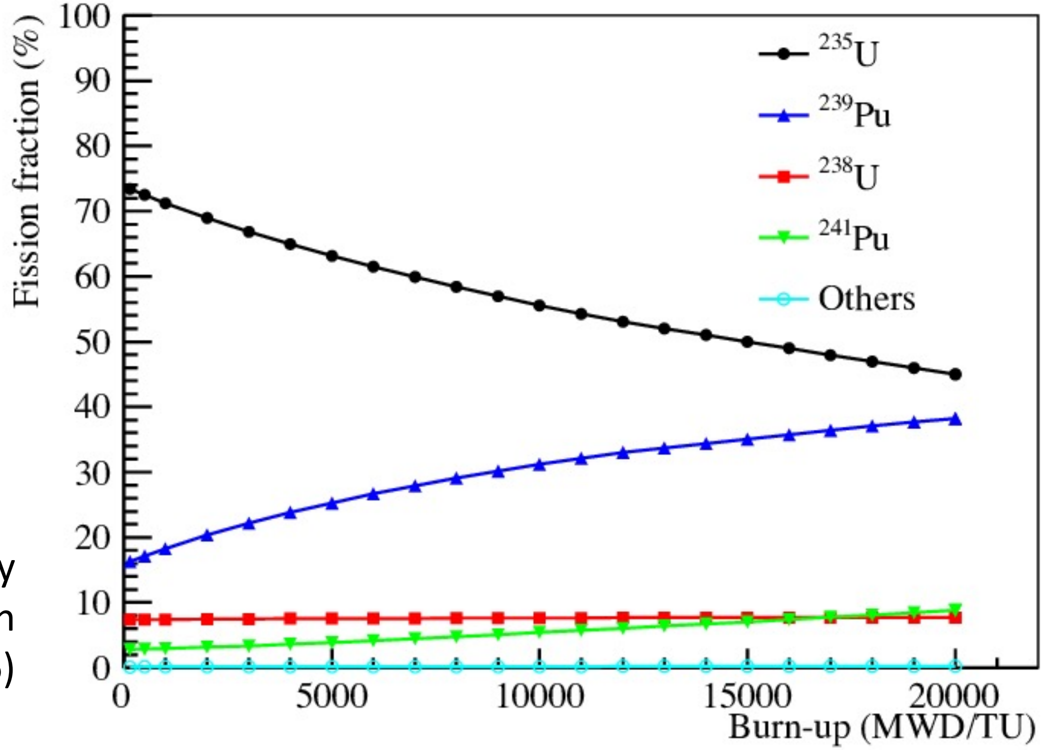
Need to know:

P_{th} = thermal power

$\langle E_f \rangle$ = mean energy per fission

f_i = fission fractions →

Fission fractions in LEU reactor vs. burnup

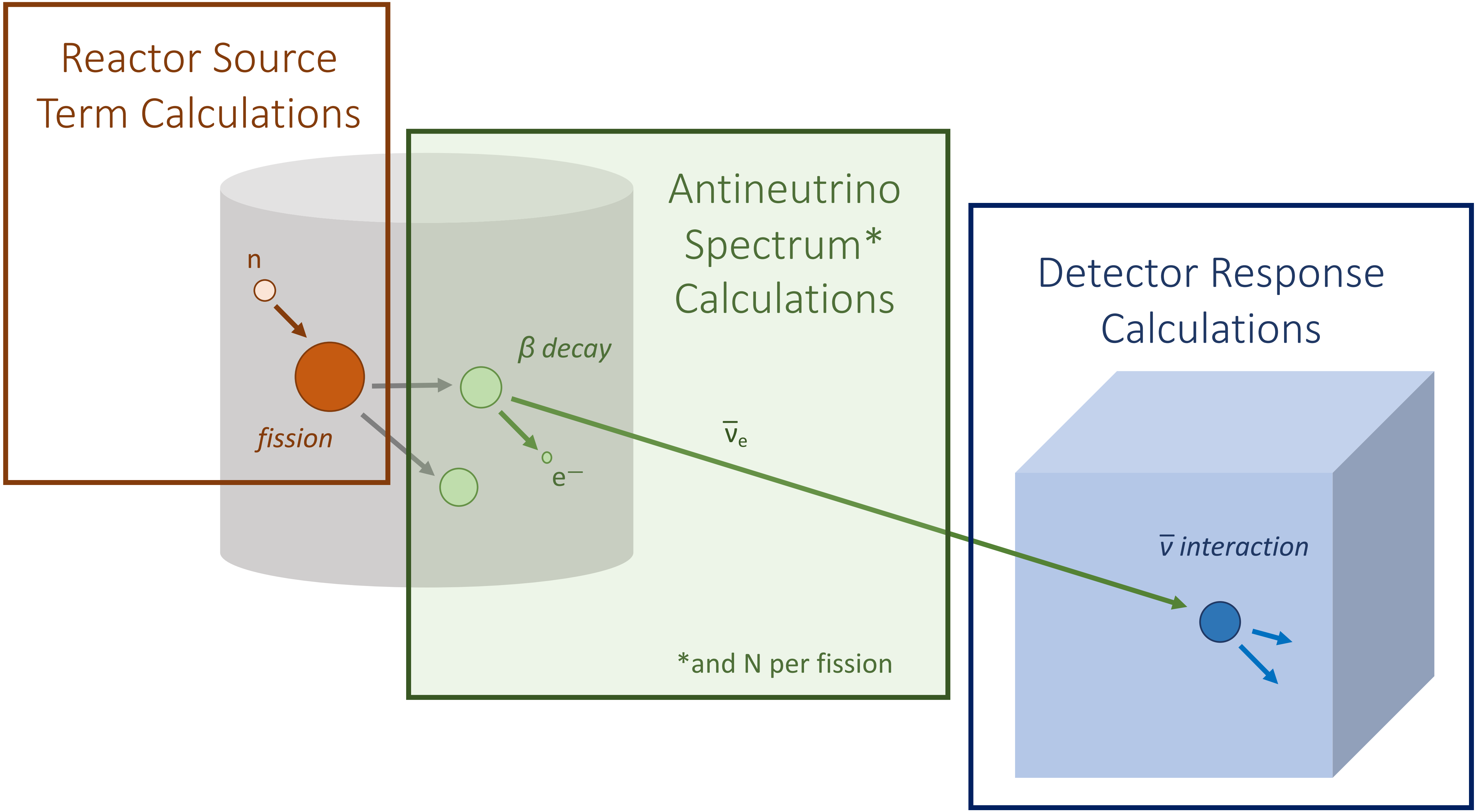


Daya Bay Collaboration (2016)

Reactor Source Term Calculations

- *Thermal power:* from reactor operator
- *Energy per fission:* from standard measurements
- *Fission fractions:* modeled through core simulations

- *Other factors:*
  - Antineutrinos from spent nuclear fuel
  - Antineutrinos from β decay after n capture on fuel/non-fuel isotope


Reactor Source Term Calculations
n
fission
Antineutrino Spectrum* Calculations
β decay
e⁻
$\bar{\nu}_e$
*and N per fission
Detector Response Calculations
$\bar{\nu}$ interaction

Antineutrino Spectrum* Calculations (*and N per fission)

- How many antineutrinos are emitted following a fission of each isotope, and what are their energies?

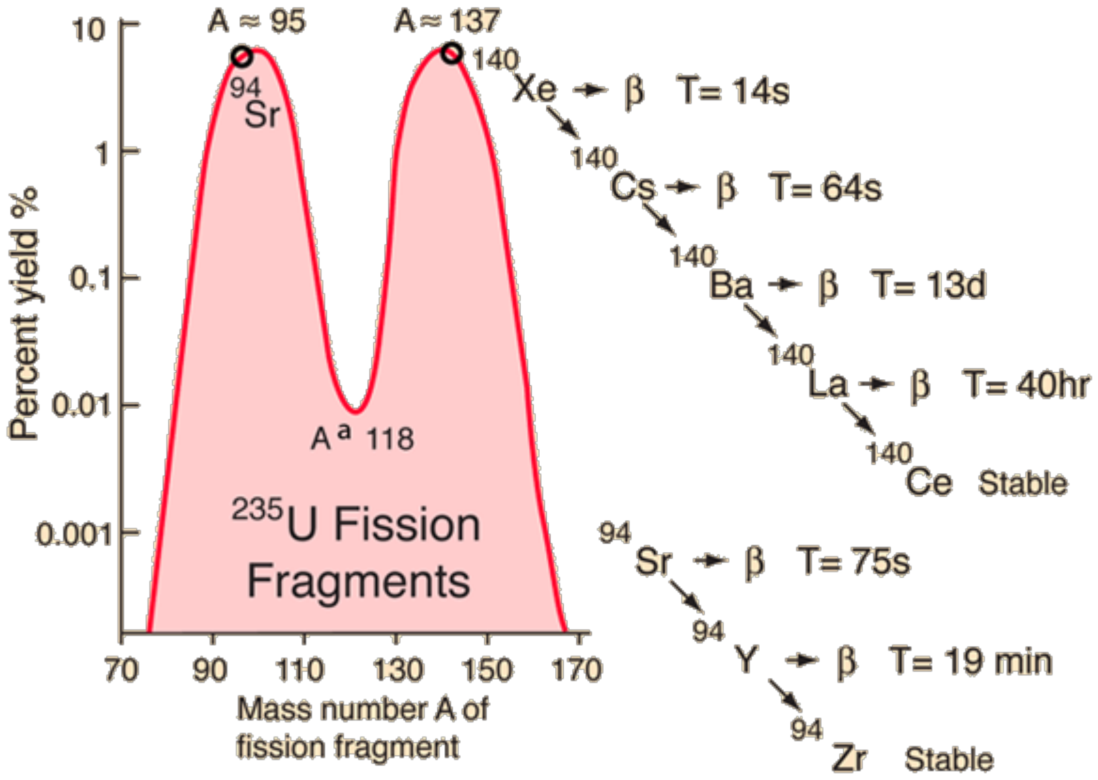


Illustration of thermal neutron fission fragment yield (http://hyperphysics.phy-astr.gsu.edu)

Antineutrino Spectrum* Calculations (*and N per fission)

- How many antineutrinos are emitted following a fission of each isotope, and what are their energies?

Two ways to approach this question:

Summation/*ab initio* approach:
Predict all the fission fragments and β decays using nuclear databases

Conversion approach:
Translate electron data → antinu emission using virtual β branches

Antineutrino Spectrum* Calculations (*and N per fission)

Summation/*ab initio* approach:
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Conversion approach:
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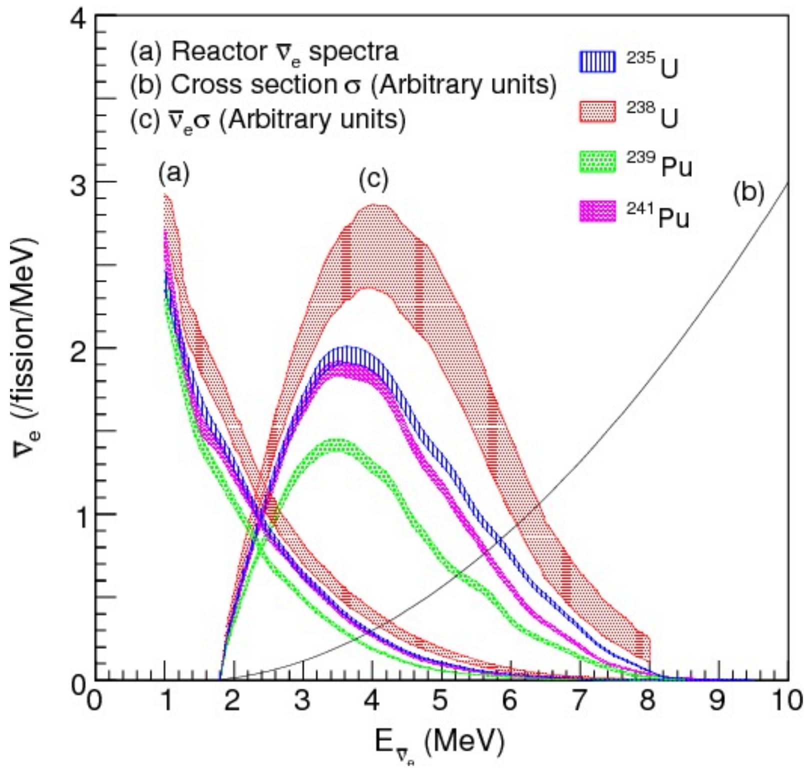
$\Phi_i(E)$ = antineutrino flux from i^{th} isotope, as function of energy

or $s_i(E)$ = flux-averaged cross section

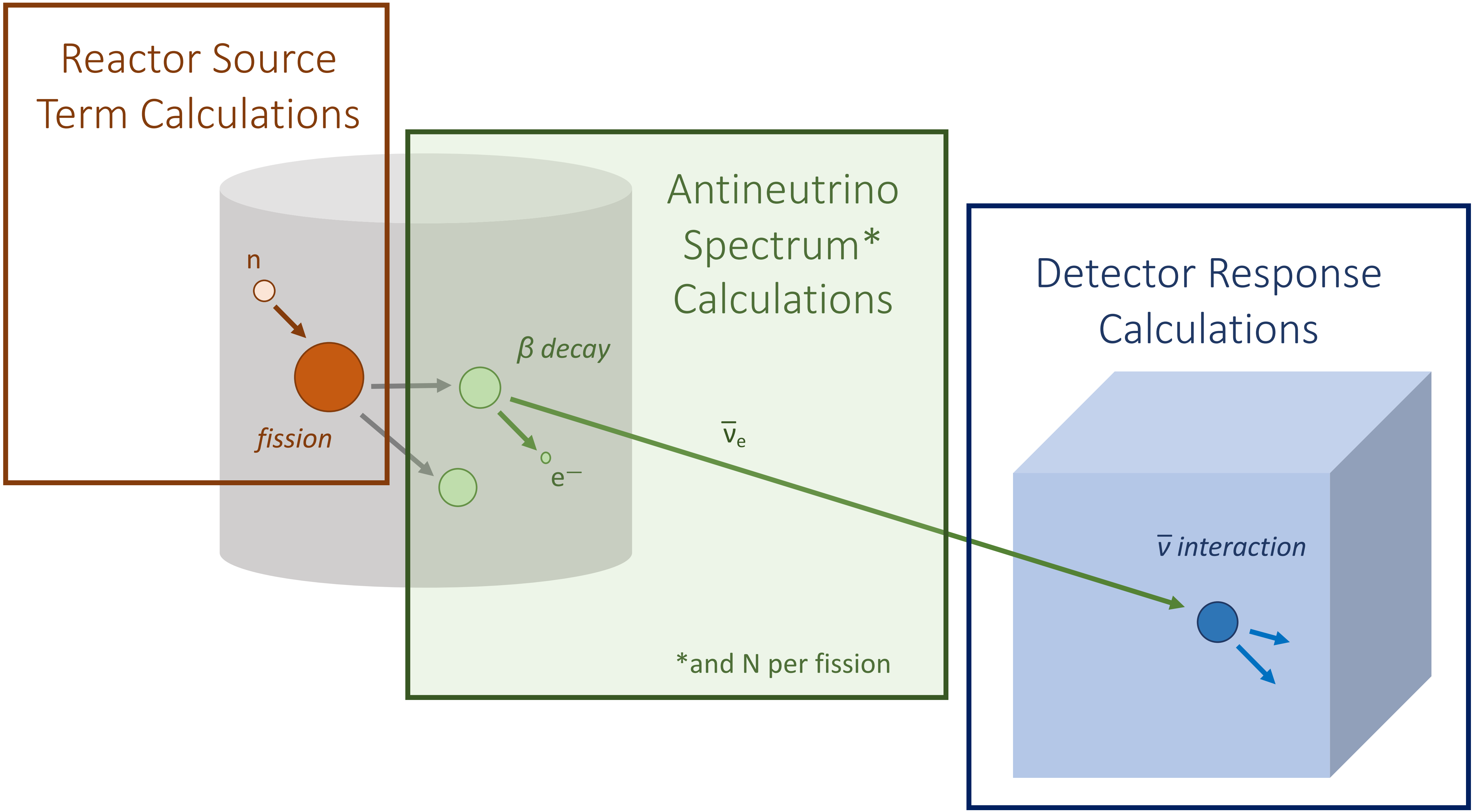


K. Nakajima *et al* (2006)

Antineutrino Spectrum* Calculations (*and N per fission)

- Both summation & conversion approaches are challenging and imperfect at present → Wednesday of WoNDRAM

- *Other factors:*
  - Non-equilibrium corrections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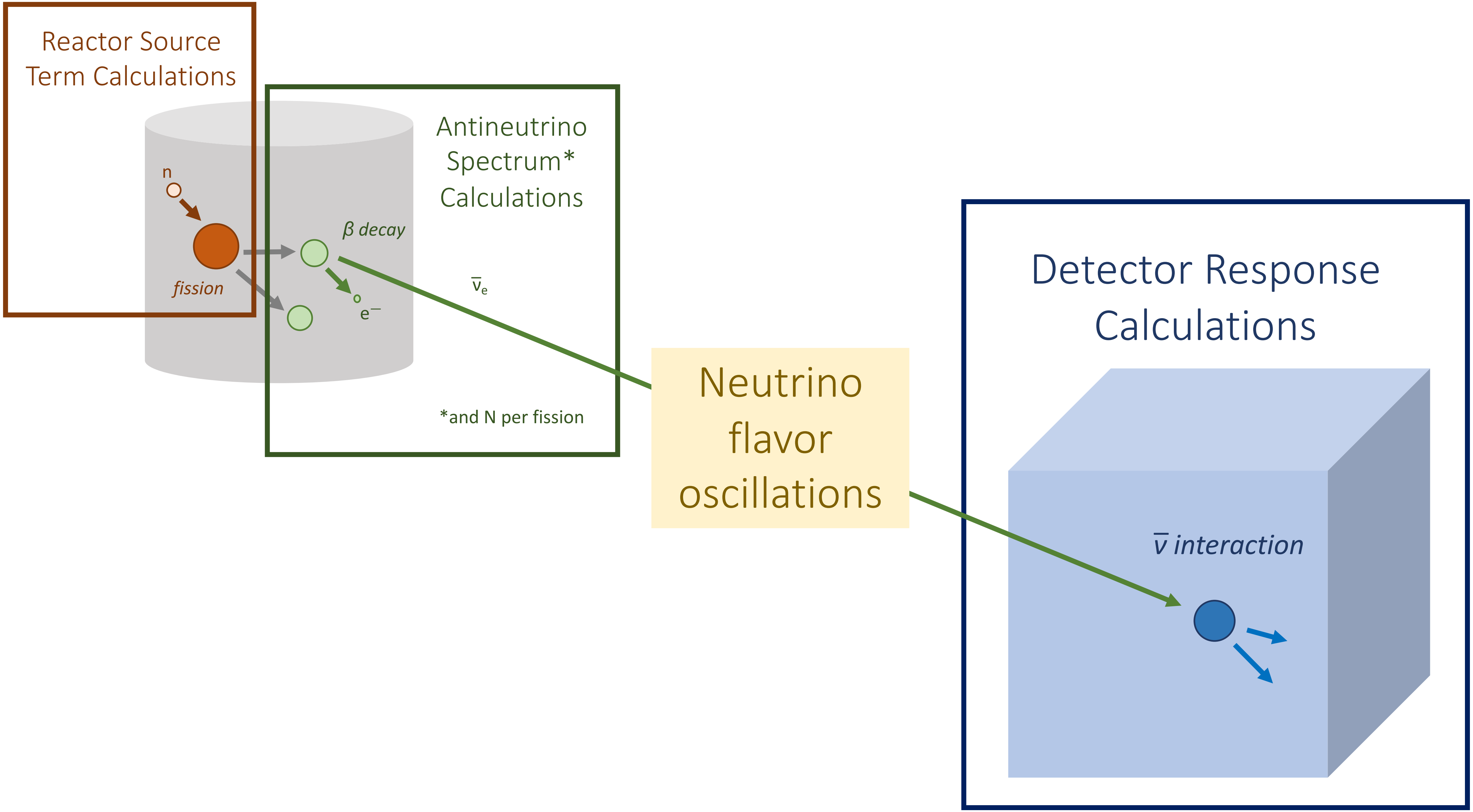
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e^-
*and N per fission
Neutrino flavor oscillations
Detector Response Calculations
$\bar{\nu}$ interaction

Neutrino flavor oscillations

- Neutrinos change flavor as they propagate, because:

Flavor states (interaction) → $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ ← Mass states (propagation)

$\nu_e \quad \nu_\mu \quad \nu_\tau$

$\nu_1 \quad \nu_2 \quad \nu_3$

↑ Mixing matrix

$$\mathbf{U} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

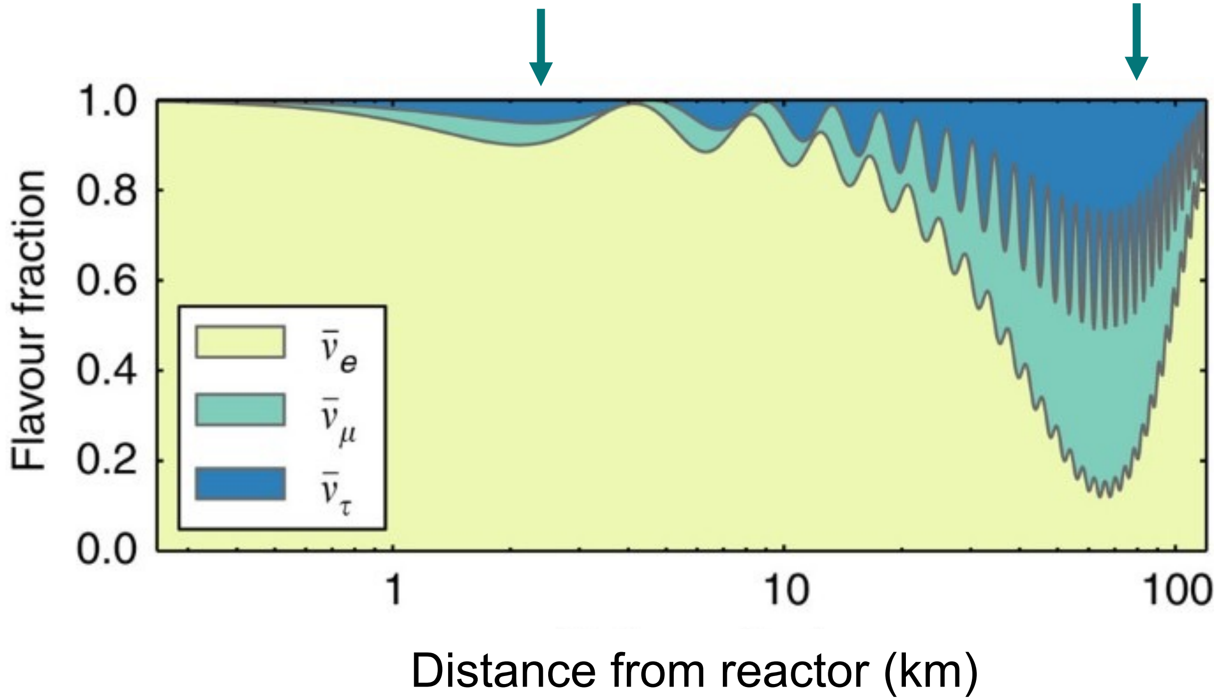
θ_{13} and θ_{12} drive reactor antineutrino flavor mixing

Neutrino flavor oscillations

- Electron antineutrinos from reactors may seem to “disappear”:

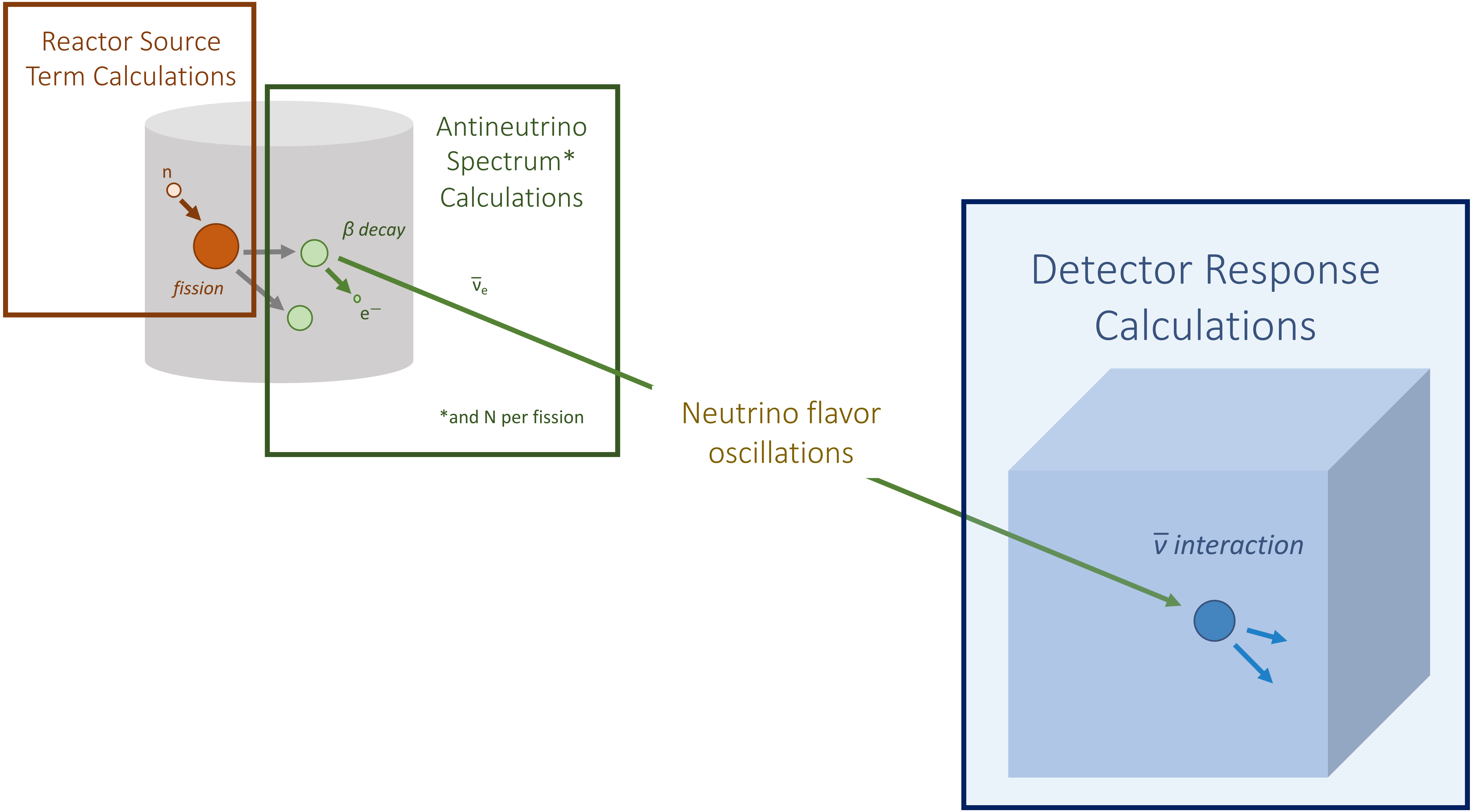
θ_{13} drives reactor antineutrino flavor mixing (“disappearance”) on distance scales O(1 km)

... θ_{12} on distance scales O(100 km)



P. Vogel *et al* (2015)

+ Sterile neutrinos driving oscillations at O(1 m)??



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Detector Response Calculations

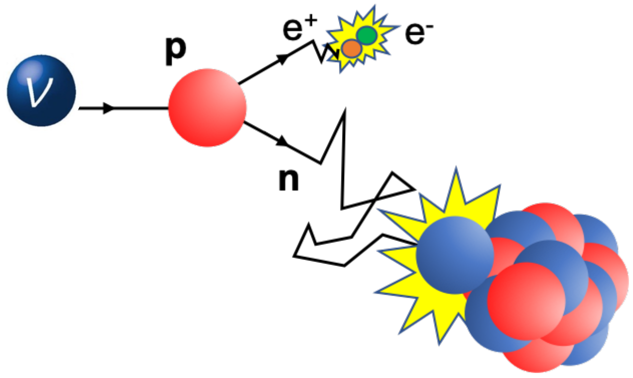
- What is the rate and energy spectrum of antineutrino interactions in the detector (and backgrounds)?

Need to know:

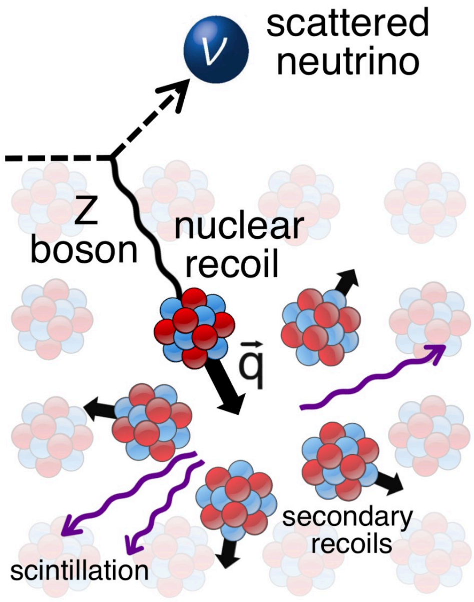
σ	=	cross section of interaction channel
N_s	=	number of scattering centers (i.e., detector size)
ε	=	signal detection efficiency
$D(E', E)$	=	detector energy response matrix
B	=	background rates & spectra

Approaches vary by interaction channel.

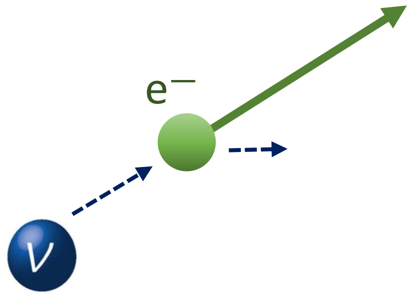
Detector Response Calculations



Inverse Beta Decay (IBD):
Scintillator (+ dopant), water + dopant



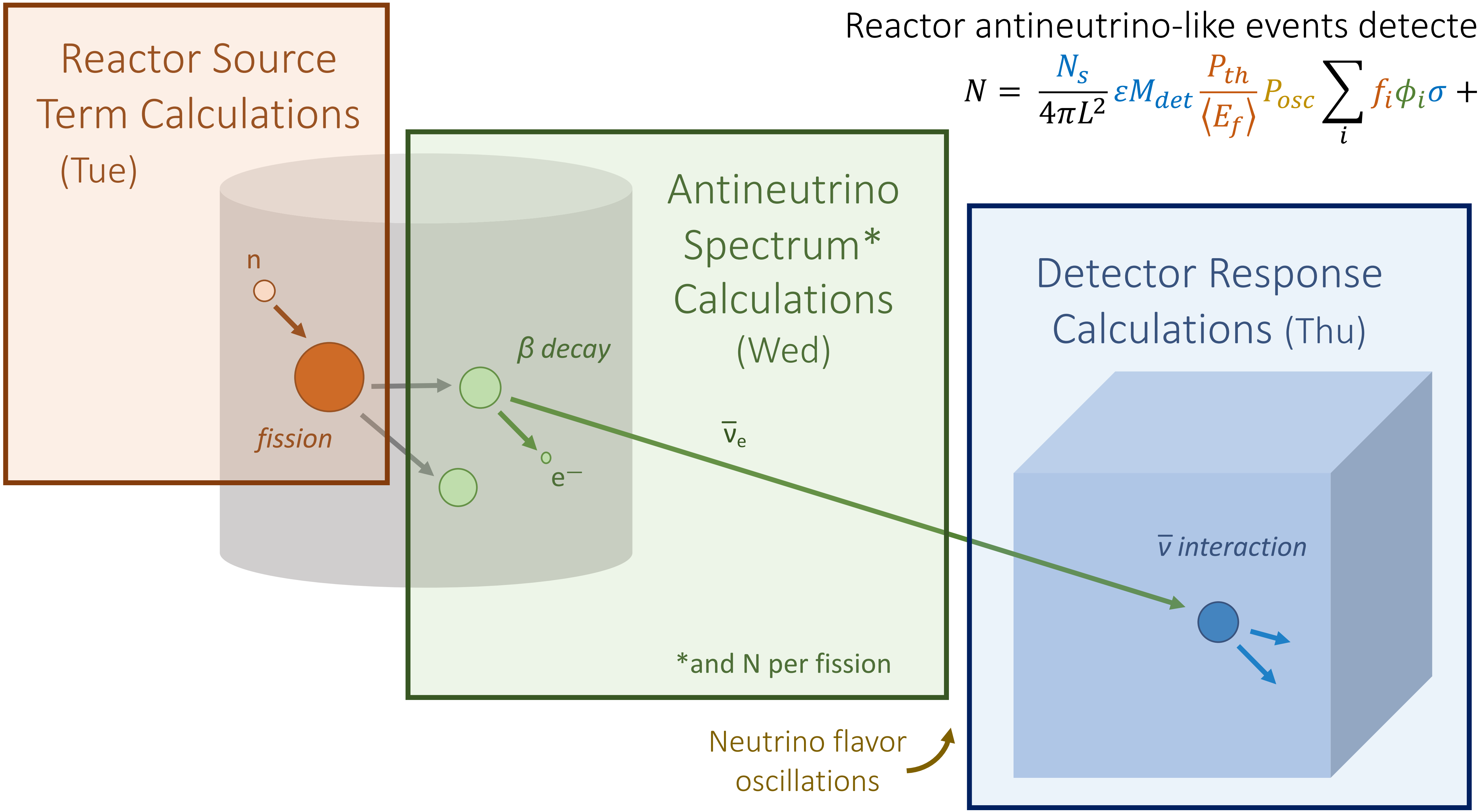
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
Scintillator, cryogenic bolometer, noble gas, ...



Electron Scattering (ES)
Scintillator, water

Reactor antineutrino-like events detected:

$$N = \frac{N_s}{4\pi L^2} \varepsilon M_{det} \frac{P_{th}}{\langle E_f \rangle} P_{osc} \sum_i f_i \phi_i \sigma + B$$



Summary

- Reactors produce $\bar{\nu}_e$ from β decay of fission fragments (brightest neutrino sources on Earth; millions of reactor antineutrinos detected).

- Reactor antineutrino emission can be modeled through calculations of reactor source term, antineutrino spectrum, and detector response. Note: Full calculation is not always needed to interpret antinu data.

- Nuclear data is important in antineutrino spectrum calculations and may also enter reactor source term and detector response calculations.